Chapter 9
Virtual Reality Reveals Mechanisms of Balance and Locomotor Impairments

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Objective To review how VR can be used to investigate normal and disturbed mechanisms of balance and locomotor control.

9.1 Multimodal Influences on Balance and Locomotor Control

Postural control requires integration of sensory information to assess the position of body in space and the ability to generate forces for controlling body position. The maintenance of upright equilibrium is essentially a sensorimotor integration task. The central nervous system (CNS) has to generate task-specific and goal-directed

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complex motor responses based on the selective and rapid integration of sensory information from multiple sources. Since each sensory system has its own coordinate framework, specific time delay, and reliability, sensory conflicts may arise and requires the CNS to recalibrate the weight attributed to each particular sensory input. Adaptive or reactive postural control involves modifying sensory and motor systems in response to changing tasks and environmental demands. Humans can tread on changing and uneven terrains without falling because the intact CNS can make ongoing corrections.

Effective postural control requires more than the ability to generate and apply forces for controlling the body's position in space. In order to know when and how to apply restoring forces, the CNS must have accurate information of where the body is in space and whether it is stationary or in motion. Somatosensory afferents provide information regarding the body's position and motion in space with respect to the support surface. Visual inputs provide information concerning the position and motion of the head with respect to the surrounding environment. With the semicircular canals sensing angular accelerations of the head in different planes and the otoliths signaling linear position and acceleration of the head with respect to gravity and inertial forces, the vestibular system provides a gravito-inertial frame of reference for postural control (Chap. 5).

9.1.1 Visual Influences on Postural and Locomotor Control

It was once thought that visual inputs were too slow to have any effect on the rapid response due to sudden perturbations of stance, since the sensation of motion induced by moving visual fields has a relatively long latency (−1 s), and the influence on body sway is too slow (Nasher and Berthoz, 1978). Subsequent experiments have shown that visual information that conflicts with those arising from other sensory channels can have a rapid and profound effect on postural responses (Keshner, Kenyon, Dhaher, & Streepey, 2004; Vidal et al., 1982). For instance, when visual inputs are stabilized with respect to the head during the time of the perturbation only, the initial triceps surae burst can be significantly attenuated and forward sway increases. In contrast, merely closing the eyes during a postural perturbation has no effect on early evoked responses or on the performance, suggesting that sensory context is an important factor in shaping the strategy for postural responses (Vidal et al., 1982). Absence of vision under these conditions does not compromise postural performance since other sensory channels provide sufficient information. In contrast, visual information that conflicts with those from other sensory channels can have a rapid and profound effect on postural responses. The influence of moving visual fields on postural stability depends on the characteristics not only of the visual environment but also of the support surface, including the size of the base of support and its rigidity or compliance (Keshner & Kenyon, 2000; Streepey et al., 2007)

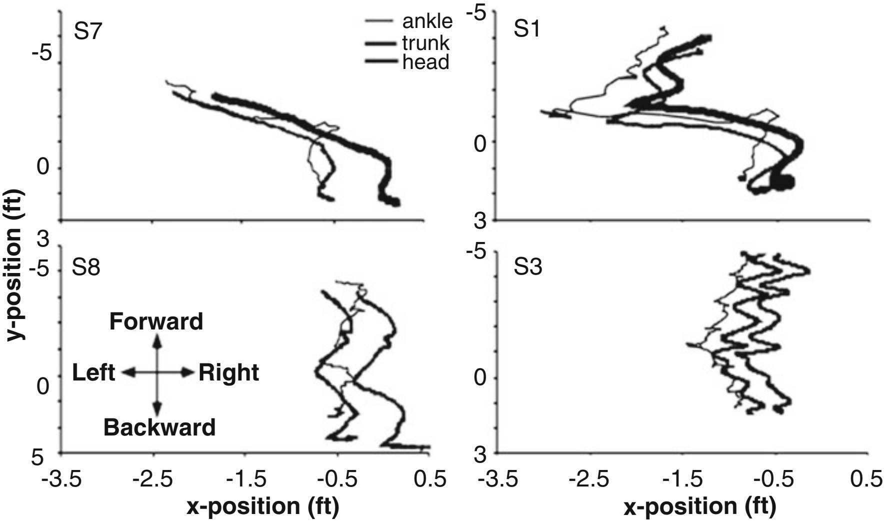


Fig. 9.1 Natural locomotion was combined with visual field motion in the roll plane with two different virtual environments (*left* and *right*). Each plot is of a different subject exhibiting one of the two response strategies in the (*top and bottom*) traces

The strong influence of a moving visual field observed on the kinematic parameters of posture and gait suggests that optic flow is an important component of the motor program when somatosensory feedback is fluctuating (Varraine, Bonnard, & Pailhous, 2002). For example, when natural locomotion was combined with visual field motion (Keshner & Kenyon, 2000; Varraine et al., 2002), kinematic parameters of gait were strongly influenced by the moving visual field (Fig. 9.1). Standing subjects viewing a wide-screen visual scene exhibited little sway when the scene was stationary, but large center of pressure (COP) changes when the scene was moving at 25°/s (Ferman, Collewijn, Jansen, & Van den Berg, 1987; Previc, 1992). Responses to visual field motion were even more strongly potentiated when body motion was added to visual field motion even though the visual inputs were incongruent with the somatosensory inputs. With only support surface translation (Keshner, Kenyon, Dhaher, et al., 2004; Keshner, Kenyon, & Langston, 2004) or tilt (Wang, Kenyon, & Keshner, 2009), segmental responses were small and mostly countering the direction of the perturbation. When the base of support and visual field disturbances were presented concurrently, however, response amplitudes became large for all subjects (Fig. 9.2). Average root mean square (RMS) values across subjects were significantly greater with combined stimuli than for either stimulus presented alone, and areas under the power curve across subjects were significantly increased at the frequency of the visual input when both inputs were presented. Kinematic changes were directly related to the velocity of the visual field (Wang et al., 2009). Therefore, virtual reality environments that manipulate the optic flow field present a compelling tool for the rehabilitation of sensorimotor disorders (Chaps. 4 and 6).

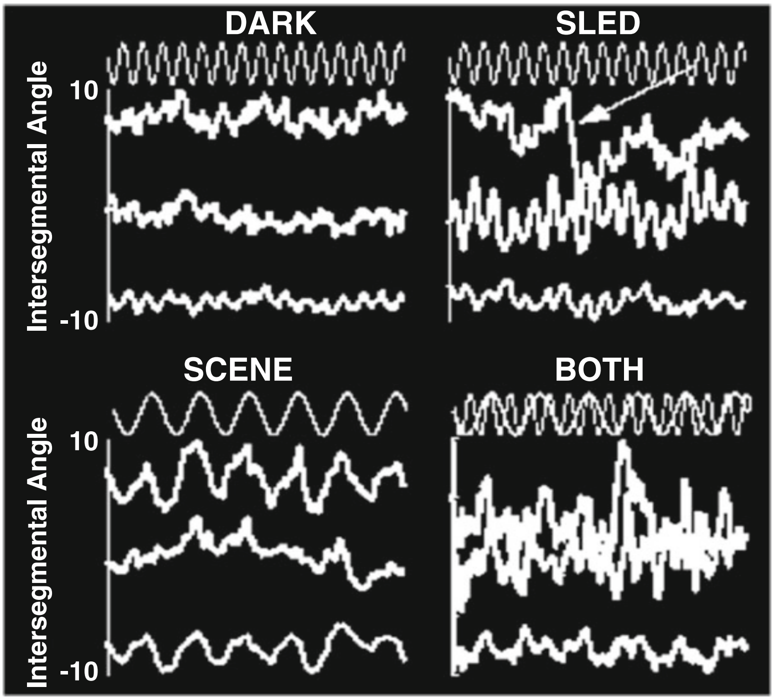


Fig. 9.2 Base of support and visual field disturbances presented concurrently (BOTH) produce more complex response behaviors than either one (SCENE or SLED) alone across 60 s of each trial. Trace above each plot is the stimulus waveform. In each plot, *top trace* is head re trunk; *middle trace* is trunk re shank; *bottom trace* is shank re platform

9.1.2 Sensory Preferences and Sensory Conflict

All of the sensory modalities are guided by, and provide updates to, a shared world model (Masumoto, Yamakawa, Kimoto, & Nagata, 1994). Conflicts between these channels have been observed through motor behaviors exhibited in the virtual world. Large movements of the visual field induce postural instability even when our bodies are not capable of performing equivalent magnitudes of motion (Dokka, Kenyon, Keshner, 2009). Both visual field velocity and direction have significant effects on the magnitude of the trunk and lower limb responses in healthy individuals (Dokka et al., 2009; Keshner & Dhaher, 2008; Keshner & Kenyon, 2000; Keshner, Kenyon, & Langston, 2004; Wang et al., 2009). Visual field motion influenced orientation of the head even when there was no physical disturbance to the position of the body suggesting a predominant impact on motion of the upper body. When conflicting self-motion from disturbances at the base of support was added to the visual field motion, kinematics of the whole body became more complex so that frequency parameters from both the visual field and the base of support motion were incorporated into the responses (Keshner, Kenyon, & Langston, 2004). Once destabilization resulting from platform motion had subsided, however, orientation of the body again became biased toward the direction of visual field motion and magnitude of joint motion increased as the visual velocity increased (Dokka et al., 2009). However, if we have prior knowledge of the characteristics of the upcoming visual motion, we are often able to reduce the size of these physical responses (Amblard, Cremieux, Marchand, & Carblanc, 1985; Day & Guerraz, 2007; Guerraz et al., 2001) from which we can infer that there is cortical control of these behaviors.

Intersensory dependencies apparent through the increased responses to the visual inputs when there were two simultaneous inputs (Keshner, Kenyon, Dhaher, & Streepey, 2005; Keshner, Kenyon, & Langston, 2004) indicate that the conflict between visual and vestibular pathways does not produce a simple switch from one modality to another. Resolving ambiguity between motion of objects in the world and motion of oneself is likely a combination of multisensorial feedback and perceptual choice and not just the identification of sensory relevance which, in the real world, may not be easily apparent (Lambrey & Berthoz, 2003). In fact, there is evidence that healthy individuals demonstrate preferences for particular sensory channels (Dumontheil, Panagiotaki, & Berthoz, 2006; Lambrey & Berthoz, 2003). When standing subjects viewed a virtual corridor in which forward movements were simulated at a constant linear velocity, and rotations were actually performed. When subjects were asked to learn the trajectory and then reproduce it from memory, half of the subjects placed more weight on visual than on non-visual information. The other subjects placed more weight on non-visual than on visual information. The difference between "visual" and "non-visual" subjects in their use of conflicting information was their own awareness of the sensory conflict. The conflicting sensory inputs were combined linearly in order to estimate the angular displacements until subjects became aware of the conflict and then produced nonlinear behaviors.

Multisensory calibration is fundamental for proficient interaction within a changing environment, but studies suggest a visual-dominant mechanism (Chap. 5). A study of both humans and monkeys performing a heading-discrimination task with either visual (optic-flow) or vestibular (motion-platform) or combined (visual–vestibular) stimuli revealed that directional adaptation of both visual and vestibular cues was required to reduce cue conflict. However, cue calibration did not depend on the reliability of the cue. Vestibular adaptation was greater than visual adaptation regardless of reliability suggesting that calibration is based on cue accuracy and that visual cue accuracy is greater than the vestibular cue accuracy (Zaidel, Turner, & Angelaki, 2011).

Visual preference, or dependence, has been measured through the "Rod and Frame" test (Asch & Witkin, 1992; Witkin & Asch, 1948). Based on performance on this test, perceptual style is classified as either field-independent or field-dependent. Field-independent individuals rely on gravitational and egocentric cues. Such individuals are able to adjust the rod to its true vertical and horizontal orientations with a high level of accuracy of about 1–2° although there is some variation in the degree to which people are influenced by the surrounding frame. Field-dependent individuals use mainly visual cues for estimating subjective vertical and body orientation.

These individuals are unable to accurately adjust the rod to its true vertical and horizontal orientations due to the influence of the surrounding tilted frame. Visual field dependence was found to be a good predictor of an individual's reliance on visual reafference to stabilize posture during Romberg stance in front of tilted visual field (Amblard et al., 1985; Isableu, Ohlmann, Cremieux, & Amblard, 1997).

9.1.3 Impact of Visual–Vestibular Conflict on Balance and Locomotion

A characteristic unique to the virtual reality environment is that it can become the observer's visual reality. This effect is more convincing when there are no cues to the physical environment, such as occurs in a CAVE or with head mounted displays (HMD). Even brief exposures to motion of a wide field of view visual environment can produce illusions of self-motion and create instability or reshape a planned movement (Dvorkin, Kenyon, & Keshner, 2009). If the environment around us is stationary, it is relatively easy to identify our physical motion. But when the world is moving, we have to determine whether it is the environment or oneself that is moving, and then shape our movements to accurately match the demands of the environment. To do this we must use the sensory information linked to the movement and identify any mismatch that may exist between the visual motion and our own sensory feedback (Dokka, Kenyon, Keshner, & Kording, 2010; Keshner & Kenyon, 2009). The perception of self-motion and orientation in space is derived from a convergence of vestibular, proprioceptive, and visual signals. Even in the physical environment, we rely on both visual and vestibular signals to define our spatial orientation and our self-motion. But when an immersive virtual environment presents no external cues to vertical, being able to distinguish between the body motion induced by visual field motion and that which is self-generated becomes a computational problem for the central nervous system (CNS) (Reymond, Droulez, & Kemeny, 2002).

This computational problem is not always accurately resolved because the perception of verticality is greatly influenced by the current optic flow field (Varraine et al., 2002; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). For example, consider the feeling of self-motion when seeing movement of a train out of the corner of your eye even though you are standing still (Previc, 1992; Previc & Donnelly, 1993; Previc, Kenyon, Boer, & Johnson, 1993; Wang et al., 2009). This illusion of self-motion generated by motion of the visual surround is called vection. An extensive literature, ranging from behavioral studies (Dichgans, Brandt, & Held, 1975; Slobounov, Tutwiler, Sebastianelli, & Slobounov, 2006; Tanahashi, Ujike, Kozawa, & Ukai, 2007; Thurrell & Bronstein, 2002) to neuroimaging studies (Brandt et al., 2002; Kleinschmidt et al., 2002; Wiest et al., 2001), has demonstrated that both vestibular and visual inputs interact at the brainstem and cortical levels during vection and that both of these sensory inputs are likely to participate in the perception of self-motion. Major characteristics of vection such as the shape of the perceived path of self-motion (e.g., linear, curvilinear, circular) and its direction are defined with respect to visual input only, as if they are independent from vestibular input. However, when visual perspective is coupled to head position, a direct linkage between the perception of vection and postural orientation is demonstrated (Keshner, Dokka, & Kenyon, 2006) suggesting a strong vestibular contribution to the perception of self-motion. In fact, onset of vection has been shown to occur more readily in subjects that do not perceive conflict between visual and vestibular afferent inputs (Lepecq, Giannopulu, Mertz, & Baudonniere, 1999), suggesting that information from the vestibular system is dominating the inappropriate visual inputs (Black, Wall, & Nashner, 1983; Keshner, Kenyon, & Langston, 2004).

Conflicting results are seen in attempts to determine whether the impact of visual information on postural reactions is due to the same perceptual mechanisms that also produce the sway resulting from the illusion of self-motion produced by an optic flow field (vection) (Clement, Gurfinkel, Lestienne, Lipshits, & Popov, 1984; Previc, 1992; Previc & Donnelly, 1993). Studies that examined body sway on a stable surface while in the Rhomberg position (Kuno, Kawakita, Kawakami, Miyake, & Watanabe, 1999; Tanahashi et al., 2007) concluded that postural sway and sway elicited by vection relied upon a shared central mechanism. When standing on an unstable support surface such as foam (Guerraz & Bronstein, 2008) or a sinusoidally moving platform (Keshner, Kenyon, & Langston, 2004) so that the direction of the two sway responses could be differentiated, postural instability occurred earlier and in the opposite direction from the later vection response.

The different time course and mismatch between the direction of postural responses and the direction of vection support a conclusion that the perceptual and postural sway responses were not generated from a single visual control mechanism (Previc & Donnelly, 1993). When subjects experienced concomitant disturbances of the visual and proprioceptive/vestibular systems, the initial recovery of vertical orientation in space was very sensitive to the dynamics of the visual field (Wang et al., 2009). Such adaptations to an active visual environment, particularly when combined with an unstable base of support, will have significant impact on the ability to maintain upright stance when negotiating challenging environmental demands, and the absence of this rapid response to visual information may contribute to postural instability in elderly individuals.

The contribution of vestibular inputs to the perception of the direction of self-motion was investigated with galvanic vestibular stimulation (GVS) on visually induced self-motion (i.e., vection) in healthy subjects (Lepecq et al., 2006). Seated subjects were submitted to optokinetic stimulation inducing either forward or upward linear vection. Subjects indicated the shape and direction of their perceived self-motion path throughout the experiment with a joystick. Results indicated that GVS induced alterations in the path of vection. GVS acts through both otolith and canal afferents (Fitzpatrick, Marsden, Lord, & Day, 2002), and thus, the linear upward or forward self-motion perception, induced by combining vection and GVS, suggests a fusion of the vestibular and visual pathways. The impact of individual sensory preferences on postural behavior are being examined in the Keshner laboratory (Keshner, Slaboda, Buddharaju, Lanaria, & Norman, 2011) by combining mismatched visual and vestibular signals by combining galvanic vestibular stimulation

Fig. 9.3 A virtual room with carpets and columns and a distant horizon and a subject standing on the dual forceplates

(GVS) with rotations of the visual field. Healthy young adults stood quietly in a 3-wall immersive stereo virtual environment (Fig. 9.3). When exposed to a moving visual field, both prior to and after application of GVS, responses at the head and COP were significantly correlated with the frequency of the visual field oscillation (Fig. 9.4, left and right). When visual motion was combined with GVS, the FFT of head angular displacement revealed responses at both the GVS and visual scene frequencies (Fig. 9.4, center). The previous 0.25 Hz response of the COP was shifted down towards 0.2 Hz suggesting that performers adapted their postural behaviors to whatever confluence of sensory information was available.

9.1.4 Effects of Visual–Vestibular Conflict with Aging and Neuromuscular Disorders

The ability to manipulate sensory conflict is particularly important when dealing with older adults and those with neurological impairment such as stroke or Parkinson's disease. With the loss of vestibular information, as occurs with destruction of the labyrinths through disease, trauma, or chemical intervention, vertigo, dizziness, and instability often result. In labyrinthine deficient patients, when visual (Bles, Vianney de Jong, & de Wit, 1983) or somatosensory (Black et al., 1983; Horak, Nashner, & Diener, 1990) information becomes unreliable, postural

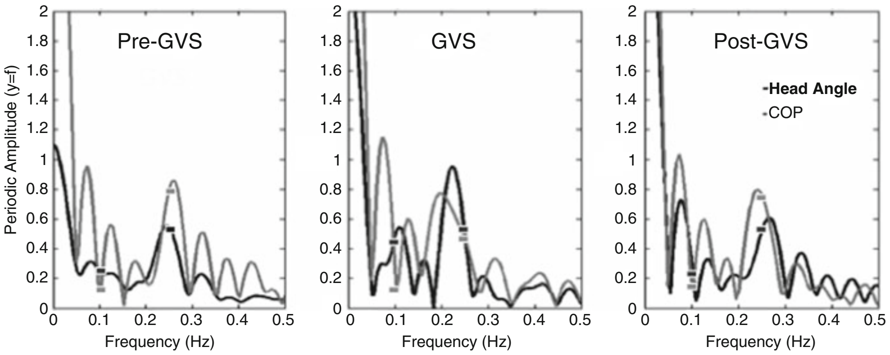


Fig. 9.4 Frequency responses of head angular displacement (*black*) and COP (*gray*) during 20 s of 0.25 Hz scene rotation (*left*), 20 s of 0.1 Hz galvanic vestibular stimulation (GVS) and 0.25 Hz scene rotation (*center*), and 20 s following GVS with 0.25 Hz scene rotation (*right*) show that GVS produced responses at the head and in the COP that were significantly correlated with the frequency of the visual field

disorientation can be explained by the fact that neither signal can adequately specify the orientation of the body in all situations.

It is not clear whether increased body sway with visual–vestibular conflict is due to optic flow streaming along the peripheral visual field, or the oculomotor motion generated by scanning the moving visual field. Studies of locomotion with combined central and peripheral radial flow have demonstrated that both central and peripheral regions of the visual field are sensitive to optic flow and will differentially influence postural stability in both healthy subjects and patients with vestibular disorders (Bardy, Warren, & Kay, 1999; Redfern & Furman, 1994; Straube, Krafczyk, Paulus, & Brandt, 1994). When elderly subjects tracked a focal object while the visual background and support surface were moving either congruently or incongruently, inappropriate peripheral visual inputs increased the amplitude of postural sway whereas appropriate peripheral visual inputs decreased postural sway (Keshner, Kenyon et al., 2004). The stabilizing effect of an object in the central visual field was altered depending upon the presence of a conflict in the peripheral visual region.

There is also evidence that the effect of visual motion on posture is modified by perceptual preference. Elderly individuals with a history of falling were significantly more visually field-dependent than those without (Lord & Webster, 1990; Slaboda, Lauer, & Keshner, 2011). Patients having cortical or sub-cortical stroke exhibited significantly larger absolute angular deviations than both healthy young and older adults for vertical and horizontal alignment of the rod even though their absolute angular deviations were highly variable between trials and within the group. Absolute angular deviations were also significantly different between older and young adults. Increased visual dependence was significantly correlated with increased postural sway when standing quietly in front of a moving visual field. Therefore, elderly adults and those with neurological impairment are more visually dependent than young adults and less responsive to somatosensory feedback, which could promote instability when vision conflicts with physical motion.

Older women in particular have been shown to be more visually sensitive than younger adults (Bugnariu & Fung, 2007; Guerraz & Bronstein, 2008; Slaboda et al., 2011). Older women exhibited significantly larger body's center of mass (COM) and COP responses in the direction of visual field motion and less muscle modulation as the platform returned to neutral than younger women. It appears that a stiffer body combined with heightened visual sensitivity in older women critically interferes with their ability to counteract postural destabilizing environments. Postural responses that are more closely matched to the visual environment but not temporally matched to the immediate demands of the postural disturbance (Dokka et al., 2010; Wright, DiZio, & Lackner, 2005) produce a greater mismatch between the visual motion feedback and somatosensory feedback and rapidly elicit spatial disorientation (Previc, 1992; Previc et al., 1993; Previc & Donnelly, 1993). In addition, postural reactions slow with aging (Gill et al., 2001; Keshner et al., 1993; Keshner, Allum, & Pfaltz, 1987; Woollacott, 1993), thereby creating even more of a window for slowly processed visual inputs to modify postural behavior.

The heightened impact of visual field motion with aging could be a significant factor in the increased occurrence of falls (Isableu et al., 2010). In addition, the changes in postural behavior in older adults as a result of visual and vestibular conflict are consistent with physiological changes of diminished vestibular sensitivity and visual acuity as we age (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Bergstrom, 1973; Peterka, Black, & Schoenhoff, 1990a, 1990b; Rosenhall, 1973). A large body of evidence also proposes that postural instability in elderly individuals is caused by their inability to process multiple simultaneous demands on attention (Shumway-Cook & Woollacott, 2000; Silsupadol, Lugade et al., 2009; Silsupadol, Shumway-Cook et al., 2009; Siu, Chou, Mayr, Donkelaar, & Woollacott, 2008; Siu, Chou, Mayr, van Donkelaar, & Woollacott, 2009; Stelmach, Zelaznik, & Lowe, 1990; Verhoeff, Horlings, Janssen, Bridenbaugh, & Allum, 2009). When faced with multiple postural demands, such as a surface that changes in gradient and frictional characteristics in a busy visual environment, compensation for one disturbance will impinge on how our responses are organized to meet successive disturbances, and this influence becomes more overpowering with aging (Slaboda et al., 2011).

9.2 Visuomotor Control of Locomotion in Virtual Reality

Virtual reality (VR) can be used to investigate normal and disturbed mechanisms of visuo-locomotor control (Chap. 8). We explain how this technology provides opportunities to manipulate visual information pertaining to self-motion and environmental characteristics as a means to investigate and shape locomotor features such as speed, trajectory, and obstacle circumvention behaviors.

9.2.1 Changing Speed Using Visual Motion Paradigms

While comfortable walking speed is determined by biomechanical, physiological, and energetic factors (Bohannon, 1997; Saibene & Minetti, 2003; Taylor, Heglund, & Maloiy, 1982), it is also influenced and monitored by the perception of self-motion of the observer with respect to its surrounding, also referred to as optic flow (Warren, 1998). Investigations on the role of optic flow in the control of walking speed were initiated in the 1990s with projections of basic luminous patterns such as spots or diamond shapes on the floor, walls, or half-spherical screens (Chou et al., 2009; Konczak, 1994; Pailhous, Ferrandez, Fluckiger, & Baumberger, 1990; Prokop, Schubert, & Berger, 1997; Schubert, Prokop, Brocke, & Berger, 2005). Experiments were repeated in rich-textured and meaningful environments, with similar results (Lamontagne, Fung, McFadyen, & Faubert, 2007; Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). Two main paradigms with distinct purposes emerge from the literature: a first paradigm that is designed to investigate *unintentional* modulations of walking speed and a second paradigm that requires the participants to *volitionally* alter walking speed based on visual perception.

9.2.2 Unintentional Modulations

Unintentional changes in walking speed is obtained by instructing participants to maintain their comfortable walking speed while having them exposed to continuous (Konczak, 1994; Pailhous et al., 1990; Prokop et al., 1997; Schubert et al., 2005) or discrete "steady-state" variations in optic flow speed (Chou et al., 2009; Francois, Morice, Bootsma, & Montagne, 2011; Lamontagne et al., 2007; Mohler et al., 2007). In most instances, the experiment takes place on a self-paced treadmill that allows the participants to change their walking speed at will. A common observation across studies is that faster optic flow causes a reduction in walking speed while slower optic flow yields a faster walking speed. Optic flow speed manipulations also shift walk-to-run and run-to-walk transitions, with faster optic flow rates eliciting lower transition speeds (Mohler et al., 2007). The proposed explanation for optic flow-induced unintentional speed modulations is that participants attempt to recalibrate the mismatch induced by the experimental manipulation between visual and body-based cues (Mohler et al., 2007; Prokop et al., 1997). Hence, a fast optic flow indicating a larger walking speed compared to that specified by body-based cues causes participants to slow down whereas a slower optic flow would do just the opposite.

Altering the speed of a visual display also modifies two features of optic flow that contribute to the perception of the speed of self-motion: global optic flow rate, referred to as the angular velocity of texture elements in a given visual direction, and edge rate, which is the number of texture elements per unit of time that pass by a reference point in a given visual direction (Francois, Morice, & Bootsma, et al., 2011; Larish & Flach, 1990). In a recent study, Francois and collaborators used a clever design based on manipulations of the participants' perceived height and density of texture elements on the floor (tiles) to dissociate the contribution of these two optic features. Both were found to contribute to walking speed modulations, with larger modifications of walking velocity being observed with the manipulations of global optic flow rate compared to edge rate. This observation indicates that both elements can potentially be manipulated in a virtual environment in order to maximize walking speed adaptations (Chap. 5).

In the context of locomotor rehabilitation, the choice of a training paradigm is guided by the nature and magnitude of the desired changes. A review of the different studies on unintentional speed modulations mediated by changing optic flows reveals that changes remain relatively modest in magnitude, that is, in the order of 10–20 % (Lamontagne et al., 2007; Pailhous et al., 1990; Prokop et al., 1997; Schubert et al., 2005). Speed adaptations are mediated through changes in both spatial and temporal dimensions, as reflected by concomitant modifications in stride length and frequency (Francois, Morice, & Bootsma, et al., 2011; Konczak, 1994; Pailhous et al., 1990; Prokop et al., 1997). Unlike normal walking with absent or congruent optic flow, however, the ratio of stride length over frequency is modified as optic flow-driven speed adaptations are predominantly induced by changes in stride length (Prokop et al., 1997; Schubert et al., 2005). In addition, modulation effects on speed were shown to diminish by 45 % over a walking distance of 800 m, indicating a habituation or, as proposed by Prokop and colleagues, a reweighting towards a more proprioceptive (spinal) control of locomotion (Prokop et al., 1997). Altogether, these observations suggest that while optic flow-based unintentional speed modulation paradigms can be useful to address matters of sensory reweighting, the modest magnitude of the speed adaptations, the altered temporal-distance relationship in stride adaptations, and attenuation of the modulation effects over time make this approach less relevant as a training paradigm to favor gait speed adaptations

9.2.3 Volitional Modulations

Lamontagne and colleagues have developed a paradigm in which participants are required to use optic flow to modulate walking speed (Lamontagne et al., 2007). It consists of having the participants walking in a short virtual corridor while presenting them with pairs of visual stimuli: a control stimulus which display an optic flow speed corresponding to the participants' comfortable walking speed followed by a test stimulus in which a steady state optic flow speed is set to a ratio (e.g., 0.25 to 2 times) of the control comfortable speed. Participants walk at comfortable speed in the control trials and are instructed, in the test trials, to walk the corridor distance within the same time as the preceding control trial. While using this gaming paradigm, an inverse linear relationship was demonstrated between optic flow and walking speed (Lamontagne et al., 2007), similar to the unintentional paradigm. As further detailed in the next section, this paradigm was proposed as a means to train walking speed adaptations in older adults, as well as in subjects with stroke.

9.3 Changing Locomotor Heading Using Visual Motion Paradigms

Heading can be broadly defined as the angular orientation, in the horizontal plane, of a motion trajectory. This section is concerned with manipulations of visual motion direction as a strategy to alter heading direction while walking. The optic flow manipulations are achieved by exposing the individuals to translating or rotating virtual environments, usually in the horizontal plane but also in the frontal plane, or by inducing a lateral asymmetry in the speed of the optic flow.

9.3.1 Manipulating Optic Flows in the Horizontal Plane

The optic flow theory stipulates that, as one moves in the environment, the flow field that is generated has a radial structure with a focus of expansion (FOE) located in the direction of self-motion which can be used to guide heading (Gibson, 1994; Warren, 1998). Warren and his colleagues were the first to demonstrate that optic flow direction information is used to guide heading during locomotion on foot (Warren et al., 2001). To do so, they offset the FOE to the side while instructing young participants to steer toward a goal and showed that the resulting trajectory in the physical world coordinates described a more or less linear path that veered away from the FOE. They also demonstrated that the reliance on the optic flow, as opposed to the visual direction of a goal (e.g., egomotion theory (Rushton, Harris, Lloyd, & Wann, 1998)), increased with greater flow and motion parallax. The latter finding suggests that providing richly textured environment to participants is ideal for enhancing or training optic flow induced steering behaviors.

In addition to the richness of the flow, its characteristics also contribute to shape steering behaviors. For instance, the larger the shift in the FOE, the larger the walking trajectory deviation in the physical walking world (Berard, Fung, McFadyen, & Lamontagne, 2009; Sarre, Berard, Fung, & Lamontagne, 2008). The structure of the flow, that is whether it is manipulated along the rotational or translational dimension, also has a profound influence on the steering behavior (Sarre et al., 2008). A translational flow that describes a lateral shift of the virtual environment lead to a steering behavior characterized by a change of locomotor trajectory that is accompanied by little reorientation of the head, thorax, pelvis, and feet, also referred to as a “crab walk” pattern (Fig. 9.5). When exposed to rotational flows, changes in the walking trajectory are accompanied by a horizontal reorientation of the head and other axial body segments in the direction of veering (Sarre et al., 2008), as observed when steering in the physical world (Grasso, Glasauer, Takei, & Berthoz, 1996; Patla, Adkin, & Ballard, 1999). These findings have a few implications that can be of interest for rehabilitation. First, by selectively shifting the FOE to one side or another, it is possible to promote veering toward a desired direction. Second, changing the magnitude of the FOE shift allows changing the extent of veering, from a

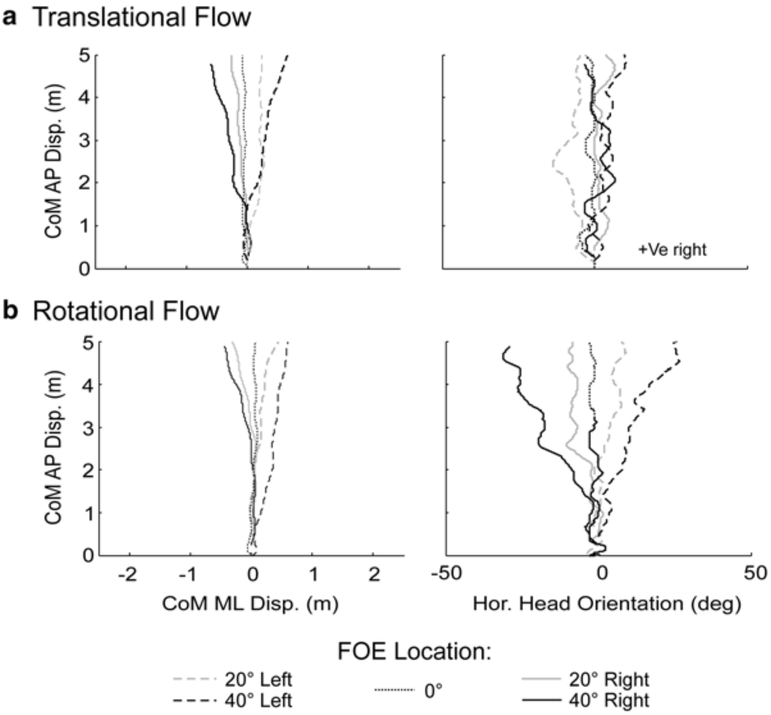


Fig. 9.5 Mediolateral displacement (*left panel*) and horizontal head reorientation (*right panel*) as a function of center of mass (COM) forward displacement in the physical world coordinates while walking in a virtual room describing optic flows having different focus of expansion (FOE) locations. The two optic flow conditions illustrated are (**a**) translational flows, where the scene was horizontally shifted to the side as the participant progressed forward, and (**b**) rotational flows, where the scene appeared as rotating around a vertical axis located at the center of the head. The participant was instructed to walk straight in the virtual world as viewed in the helmet mounted display. Note that both translational and rotational flows induced a walking deviation in the direction opposite to the FOE. This change in trajectory was accompanied by a horizontal head reorientation for the rotational flow (**b**) but not for the translational flow (**a**). This figure was modified from (Sarre et al., 2008)

small to a larger deviation. Finally, while the rotational vs. translational dimensions of the flow allows for selective steering behaviors in terms of body segment coordination, rotational flows appear to describe more ecological and commonly encountered visual stimuli, as when walking along a curved path, which in turn induces a more natural steering behavior.

9.3.2 *Optic Flow Speed Asymmetry and Visual Roll*

Other visual motion stimuli that were used to manipulate locomotor heading include lateral asymmetries in optic flow speed as well as visual roll stimulation. In the optic flow speed asymmetry paradigm, individuals exposed to different speeds of optic flow projected onto a right vs. left wall veer or drift away from the faster moving wall, with larger speed differences leading to larger lateral drifts (Chou et al., 2009; Duchon & Warren, 2002). A roll of the virtual environment at constant speeds ranging from 5°/s to 15°/s also lead to a lateral deviation of the walking trajectory (Keshner & Kenyon, 2000; Schneider, Jahn, Dieterich, Brandt, & Strupp, 2008). This walking deviation, which is towards the left in presence of a counter-clockwise rotation and towards the right for a clockwise rotation, could be mediated by an altered perception of verticality, as well as the sense of vection provided by the stimulus (Keshner & Kenyon, 2000; Schneider et al., 2008). The effects of a visual roll stimulation on the walking deviation can be overridden by some individuals (Keshner & Kenyon, 2000) and disappears after a walking distance beyond 2 m (Schneider et al., 2008), which suggests the presence of a sensory reweighting toward non-visual sources of information. It should be noted, however, that no such observations were reported in studies where participants were clearly instructed to control their heading within the *virtual world* coordinates (Berard et al., 2009; Warren et al., 2001). The instructions provided to participants, especially in a context where the sensory information specified in the virtual vs. physical world is incongruent, can be a key factor that contributes to shape the steering responses.

9.3.3 Adaptations to Repeated Exposure

Another issue that is of interest to rehabilitation concerns the effects of a prolonged exposure to a stimulus, as in the context of a training session (Chap. 3). When aiming at a virtual target while exposed to a rotating (yaw) optic flow over repeated walking trials, heading errors with respect to the target decrease, especially within the first 10 trials, provided that the adaptation is done overground to allow the participants to adjust their walking trajectory (Bruggeman, Zosh, & Warren, 2007; Saunders & Durgin, 2011). These results suggest the presence of a learning effect with repeated exposure. Full-field or richer optic flow conditions allow for faster and larger heading adaptations (Bruggeman et al., 2007; Saunders & Durgin, 2011), further supporting the idea that rich visual environments may be optimal for rehabilitation. A prolonged (20 min) or repeated (20 trials) exposure to a horizontal rotational flow while walking either overground or on a treadmill were reported to be sufficient to yield after-effects that are characterized by a change in torso orientation and heading direction (Mulavara et al., 2005; Nomura, Mulavara, Richards, Brady, & Bloomberg, 2005; Saunders & Durgin, 2011). Whether this after-effect persists over time and could thus be used for therapeutic purposes remains unknown.

9.4 Obstacle Avoidance Paradigms

When walking, individuals also need to adapt their locomotor behavior to environmental constraints that can present in the form of changing terrains, luminosity as well as presence of static and dynamic bodies. Obstacle circumvention abilities can be altered by various conditions such as post-stroke visuospatial neglect (Punt, Kitadono, Hulleman, Humphreys, & Riddoch, 2008; Webster, Rapport, Godlewski, & Abadee, 1994), traumatic brain injury (Fait, McFadyen, Swaine, & Cantin, 2009), or simply older age (Gerin-Lajoie, Richards, & McFadyen, 2006; Paquette & Vallis, 2010), leading to an increased risk of collisions and limited mobility in the community. The VR technology, because of its configurability, reproducibility, and safety, is an ideal tool to investigate and train complex visuo-locomotor tasks, especially when using a moving obstacle paradigm that would otherwise be challenging to design and control in a physical environment. Yet very few VR studies in this area are so far available, especially in individuals with disabilities. The section below highlights the salient findings from these few studies and introduces new perceptuomotor paradigms developed in our laboratory which could help provide insights into the altered obstacle circumvention abilities presented by individuals with perceptual or motor problems.

The first studies that used the VR technology to investigate locomotor adaptations to virtual objects emerged from the field of psychology and have proposed different mathematical models to capture behaviors during interceptive, steering, and obstacle circumvention tasks (Chardenon, Montagne, Laurent, & Bootsma, 2004; Cutting & Vishton, 1995; Fajen & Warren, 2003). When both the participant and virtual object of interest are moving, as when intercepting a moving ball while walking, the locomotor adaptations depend on multiple sources of optical information, including the global optic flow perceived at the eye of the moving participants, the local optic flow due to the ball movement and the egocentric position (non-flow information) of the ball (Chardenon et al., 2004; Cutting & Vishton, 1995; Fajen & Warren, 2003). It is proposed that interceptive, steering, and obstacle circumvention tasks would rely on similar optical information and share a similar architecture of control law (Chardenon et al., 2004; Fajen & Warren, 2003; Fink, Foo, & Warren, 2007).

A first question of interest to the field of rehabilitation concerning obstacle circumvention in virtual environments is whether it resembles that observed in the physical world. Features that are peculiar to the VR technology and that may influence obstacle circumvention include, but are not limited to, a lack of physical consequence in presence of a collision, a greater uncertainty about the position of virtual objects and that of the participant, as well as a perceived distance compression (Chap. 4, Fink et al., 2007). In two studies that compared circumvention strategies of young adults in response to real vs. virtual static obstacles, it was found that the curvature and shape of the participants' trajectory was the same but that subjects maintained slightly larger distances from the obstacles in the virtual world compared to the physical world (Fink et al., 2007; Gerin-Lajoie, Richards, Fung, & McFadyen, 2008). This similarity in terms of strategy, at least for young adults walking in the presence of static obstacles, suggests that obstacle circumvention paradigms in virtual environments can be used for evaluation and training purposes and may translate into improvements in the physical world.

By varying the characteristics of the obstacles, it was also shown that the perception of a potential collision and the actual avoidance strategies can be modified. For instance, changing the proximity at which a virtual pedestrian will pass with respect to the participant impacts on the ability to detect a potential collision (Ouellette, Chagnon, & Faubert, 2009). Indeed, while predictions are highly accurate for "head-on" approaches and reasonably good when the virtual pedestrian passes at ±10° on either side of the participants' shoulders, there is much more uncertainty, hence larger errors, when the pedestrian passes close (±5°) to the participants. The side of approach also makes a difference with larger errors in collision prediction being reported for moving obstacles passing to the right (Ouellette et al., 2009) and larger clearances when circumventing a static obstacle towards the left (obstacle on the right) (Gerin-Lajoie et al., 2008). The latter observations indicate the presence of asymmetries in terms of perceptual and motor responses to right vs. left obstacles, which have to be taken into consideration when dealing with populations with unilateral sensory and/or motor disorders such as a stroke. Finally, although this is yet to be confirmed in virtual environments, circumvention strategies remain the same for static vs. dynamic obstacle but are characterized by later onsets in terms of step pattern modulation and smaller clearances with dynamic obstacles (Gerin-Lajoie, Richards, & McFadyen, 2005, 2006). The number of obstacles can also add to the complexity of the locomotor adjustments (Berard & Vallis, 2006) and the addition of distractors that challenge attentional resources can impact on the task performance (Gerin-Lajoie et al., 2006). A VR training paradigm for obstacle circumvention can thus be graded in complexity, starting with environments where obstacles have an easily identifiable risk of collision and where the presence of distractors and locomotor adjustments are minimized, and progressing to scenarios where perceptual, attentional, and motor demands become increasingly challenging.

9.4.1 Investigating Perceptuo-motor Strategies with Visuospatial Neglect

The ability to perform a circumvention task depends on the integrity of the perceptual, motor, and cognitive systems. We have recently developed a series of experiments that allow investigating the perceptual and motor strategies used by healthy individuals (Darekar, Lamontagne, & Fung submitted) and subjects with post-stroke visuospatial neglect (Aravind & Lamontagne, 2012). These experiments probe questions such as: How early is an obstacle movement perceived in the virtual environment? Are perceptual abilities related the persons' ability to avoid an obstacle while walking?

We have recently tested 12 subjects in a virtual environment consisting of a room with 3 obstacles, one of which randomly approached from head-on or 30° to the left or right (Aravind & Lamontagne, 2012). Subjects pressed a joystick button on perception of a moving obstacle in the perceptuo-motor task and walked toward a target while avoiding a collision with the moving obstacle in the walking task. Detection times in the perceptuo-motor task and minimum distances maintained from the obstacles in the walking task were examined. Results indicate that more than half ($n = 7$) of the participants with neglect showed longer detection times (28 %) in the perceptuo-motor task as well as smaller minimal distances (−35 %) and higher collision rates (140 %) in the walking task when the obstacles approaching from the contralesional side compared to the ipsilesional side. These participants also avoided steering toward the contralesional side in 90 % of the walking trials, irrespective of the obstacle approach. Other participants with neglect showed less severe alterations and asymmetries in their performance for the ipsilesional and contralesional obstacles. More recent analyses revealed that the total number of collisions while walking was moderately associated with the ability to detect the obstacles on the contralesional side (Pearson's $r = 0.64$, $p < 0.05$), but not with the number of omissions on the Bell's test, a clinical test for visuospatial neglect. These results indicate that obstacle circumvention abilities are affected by visuospatial neglect, thereby confirming several anecdotal reports of an increased risk of collisions with objects in this population. With virtual reality, it was possible to establish a relationship between the participants' perceptuo-motor and locomotor performances in a similar, controlled environment. The lack of relationship between the walking performance and the clinical "pencil and pencil" test for neglect further emphasizes the utility of virtual reality which can provide task-specific and functionally relevant environments in which perceptual and motor strategies can be assessed, and eventually trained.

9.5 Effects of Optic Flow and on Elderly and Neurologically Impaired Individuals

9.5.1 Modifying the Speed of Optic Flow

A few research groups have examined the effects of aging and CNS lesions on optic flow-driven speed modulation patterns. A common observation is that unintentional speed modulations are preserved in older adults (Chou et al., 2009; Konczak, 1994; Schubert et al., 2005). With the occurrence of a stroke, however, unintentional speed modulations are attenuated compared to healthy controls (Lamontagne et al., 2007). Changes are not attributable to the patients' functional gait capacity (Lamontagne et al., 2007) but may be explained by an altered perception of speed of visual motion information (Vaina et al., 2010) or defective sensorimotor integration (Lamontagne, Paquet, & Fung, 2003). At variance, individuals with Parkinson's disease show exaggerated responses to changing optic flow speeds (Schubert et al., 2005). Furthermore, they do not present with the attenuation over time of the speed responses that is normally observed in healthy adults. According to Shubert and collaborators, the abnormal speed responses observed in Parkinson's disease could be explained by the presence of deficits in proprioception that were likely compensated by a reweighting of visual kinesthesia (Schubert et al., 2005).

When engaged in volitionally using optic flow speed information to adapt their walking speed, young individuals do very well, as illustrated by a strong inverse relationship between optic flow speed and gait speed with a slope that approaches −1

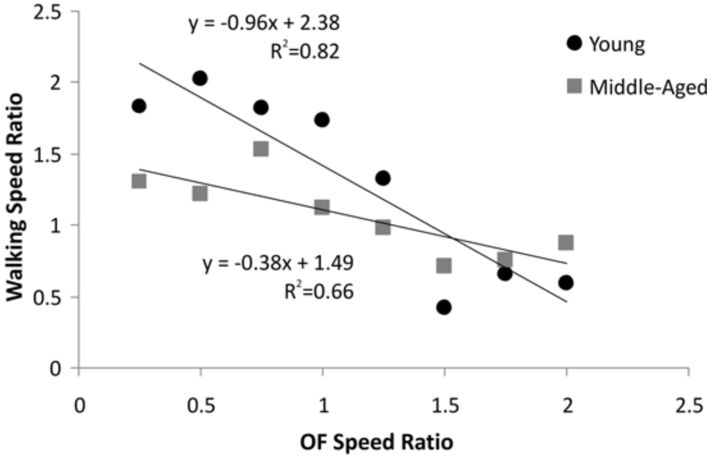


Fig. 9.6 Changes in walking speed in one young (27 YO) and one middle-aged individual (53 YO) walking on a self-pace treadmill while watching a virtual corridor of changing optic flow speed in a helmet mounted display. Values are expressed as ratios of the speed measured during comfortable walking. Linear regression equations and corresponding coefficients of determination (R^2) are illustrated for each participant. Note the attenuated slope in the middle-aged individual compared to the young adult

(Fig. 9.6). Older individuals that can be qualified as "young-old" (mean age 67 ± 4 years), however, already show attenuated speed responses compared to their younger counterpart (Lamontagne, Fung, Paquette, Faubert, & McFadyen, 2005).

Similarly, in a study that also involved controlling speed of self-motion but during a joystick driven locomotor interceptive task, middle-aged individuals (mean age 58 ± 2 years) displayed abnormally large errors compared to younger adults (Francois, Morice, Blouin, & Montagne, 2011). Performance at visuo-locomotor tasks that require the processing of visual motion speed can thus start deteriorating early in the process of aging. Potential explanatory factors include an altered perception of visual motion (Norman, Ross, Hawkes, & Long, 2003; Snowden & Kavanagh, 2006), slower information processing (Salthouse, 2000; Welford, 1988), and an altered sensorimotor integration. Interestingly, it is worth mentioning that while older adults were consistently reported to show exaggerated postural responses to moving visual surrounds (Bugnariu & Fung, 2007; Simoneau et al., 1999; Slaboda et al., 2011), they can at the same time experience a reduced sense of vection (Haibach, Slobounov, & Newell, 2009), suggesting that an enhanced susceptibility to visual motion information can coexist with an altered perception or utilization of visual motion during postural or locomotor tasks.

Individuals with stroke display volitional gait speed modulations that are within the range of age-matched control values, even when presenting with severely reduced gait capacities (Lamontagne et al., 2007), which suggest that the volitional paradigm has potential for training speed adaptations in this population. In fact, this paradigm was recently integrated in a VR training regimen to promote balance and faster walking speeds in subjects with chronic stroke (Kang, Kim, Chung, & Hwang, 2012).

9.5.2 Modifying the Direction of Optic Flow

Similar to optic flow speed, changing optic flow direction elicit changes in locomotor behaviors, which can be altered by aging and the occurrence of central nervous system pathologies. Berard and collaborators demonstrated that young-old adults (mean age 66 ± 4 years) failed to modify their walking trajectory in response to translational optic flows of changing direction, indicating a pronounced effect of aging, even at its very early stage (Berard et al., 2009). While this information is consistent with the altered discrimination abilities of older adults for the direction of radial or translational visual motion (Ball & Sekuler, 1986; Warren, Blackwell, & Morris, 1989), evidence of a relationship between visual motion perception and heading adaptations to visual motion while walking is still lacking.

At variance with translational optic flows, rotational flow stimuli do yield some degree of heading modulation in older adults, possibly due to the more "ecological" nature of the rotational flow stimuli for which the processing may be partially preserved with older age (Berard, Fung, & Lamontagne, 2011). In individuals with stroke, patterns of steering behaviors in response to both rotational and translational flows are altered and include reduced, absent, as well as asymmetrical patterns of responses that are biased either towards the paretic or non-paretic side (Berard, Fung, & Lamontagne, 2012; Lamontagne, Fung, McFadyen, Faubert, & Paquette, 2010). A history of visuospatial neglect, where symptoms are apparently resolved based on standard neurophysiological assessments, would be a common hallmark of stroke participants displaying either reduced or asymmetrical steering responses (Berard et al., 2012). This suggests that persistent visuospatial neglect, especially for far space and/or dynamic visual cues, may not be detected through conventional static pen and paper tests and should be addressed using ecological virtual environments where dynamic visual information about near and far space is integrated.

9.6 Sensorimotor Conflicts Support Virtual Reality as a Rehabilitation Tool

VR can be a valuable tool for therapeutic interventions that require adaptation to complex, multimodal environments (Chaps. 3 and 6). When designing VR protocols involving multisensory modalities, one should be aware of the potential of sensory conflicts and their effects. Conflicting visual and somatosensory stimuli can modulate automatic postural responses in both healthy young and old adults (Bugnariu & Fung, 2007). Aging affects the interaction of the somatosensory and visual systems on the ability of the CNS to resolve sensory conflicts and to maintain upright stance equilibrium.

Visual dependence may be a compensatory strategy for coping with poor balance post stroke. Compounding effects of age and neurological injury can skew the sensory recalibration processes required for resolution of sensory conflicts toward an excessive reliance on visual inputs. In addition to motor impairment, postural imbalance in patients with hemiparesis may be caused not only by elementary sensory impairment (visual, somatosensory, vestibular) but also by the inability to resolve sensory conflicts and to select pertinent sensory information. Thus, excessive reliance on vision may become problematic when the visual information is not reliable.

In a study that investigated the effects of aging and stroke on the capability of the CNS to select appropriate sensorimotor strategies and regulate balance while under conditions of sensory conflict created by VR, both young and older adults were tested during quiet stance while wearing a helmet-mounted display (HMD, Kaiser Optics ProView™ XL50). Subjects were exposed to random visual and/or surface perturbations consisting of ramp-and-hold tilts under four conditions: (1) visual-only; (2) surface-only; (3) discordant where visual perturbation was combined with synchronized surface perturbation in the same direction, and (4) concordant where visual perturbation was combined with synchronized surface perturbation in the opposite direction.

During visual-only perturbations, minimal displacements of COP and COM were observed in both subject groups (Figs. 9.7 and 9.8). The presence of sensory conflicts in surface-only and discordant perturbations induced significantly larger COM excursions than concordant perturbations in both young and old adults. However, the presence of sensory conflicts required a larger correction in older adults.

Average EMG latencies of ventral muscles during surface-only, discordant, and concordant perturbations in young and old adults are shown in Fig. 9.9. In young adults, muscle recruitment generally followed a distal-to-proximal sequence, regardless of perturbation direction or sensory conflicts. In older adults, the distal-to-proximal sequence of EMG activation was less consistent, especially under sensory conflict, during surface-only and discordant perturbations where a reverse sequence was observed (Fig. 9.9). Generally, the EMG onset latencies of older adults, which were already delayed as compared to young adults, were further prolonged in conditions of sensory conflict. Thus, the presence of sensory conflict had a larger impact on the selection of appropriate strategies for balance control in older adults.

Similar age-related postural instability was reported by Mahboobin, Loughlin, Redfern, & Sparto (2005) who showed that optic flow induced larger postural responses in older subjects than in subjects who had adapted from unilateral loss of vestibular function. It is plausible that delayed or diminished vestibular and somatosensory inputs in older adults increases their sensory thresholds to complex multimodal stimuli, thereby inducing a greater reliance on visual inputs and making it more difficult for them to respond selectively to visual and physical destabilization. However, we must consider that the use of a HMD to deliver the visual perturbation might have also limited the influence of visual inputs. Postural responses coupled with optic flow are less frequent when the optic flow is delivered in a central field of view, like the HMD, as compared to large field of view display (Sparto et al., 2006; Whitney et al., 2002).

The effects of aging and sensory motor deficits following stroke on the capability of CNS to select pertinent sensory information and resolve sensory conflict created by virtual reality were also examined in subjects with chronic stroke and age-matched healthy old adults (Fig. 9.10). With repeated exposure to VR-induced sensory conflict,

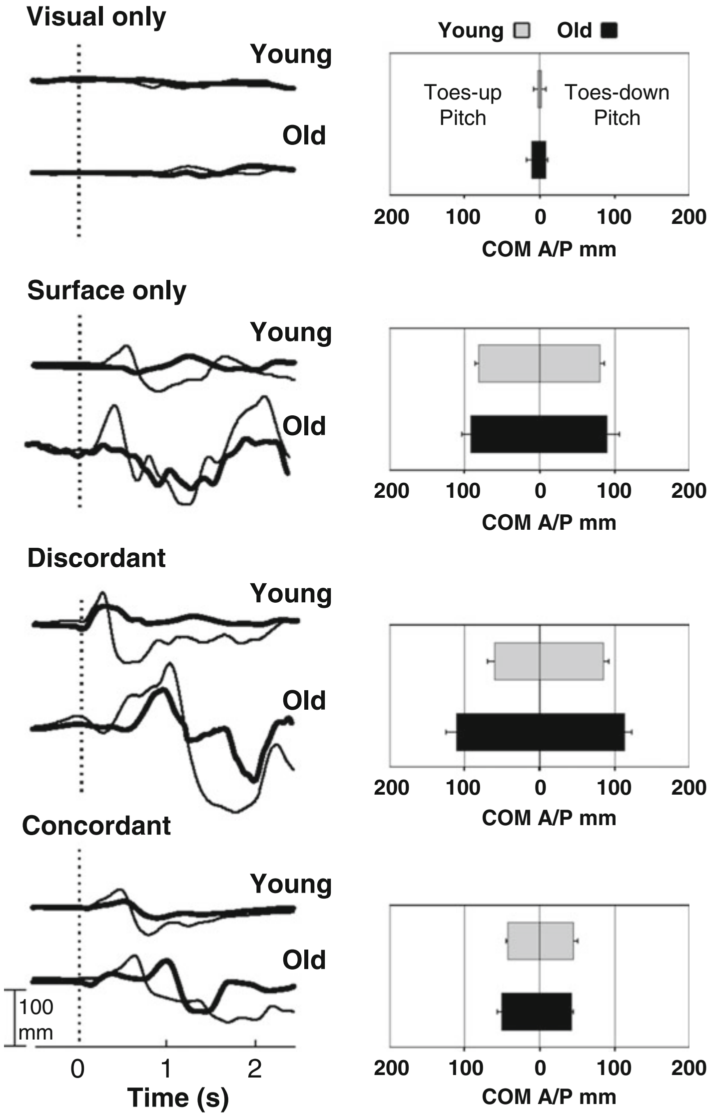


Fig. 9.7 Representative example of individual traces of COP (*thin lines*) and COM (*thick lines*) from one young and one old subject (*left panel*) exposed to toes-up tilt of the surface. Bar graphs on the *right panel* show COM peak-to-peak excursions (mean ± SD) averaged across 10 young subjects (*gray bars*) and 10 older subjects (*black bars*) in both toes-up (*left column*) and toes-down (*right column*) directions

a general training effect associated with fewer stepping responses and improved ability to maintain balance was observed in older adults but was less evident in stroke subjects. Stroke subjects exhibited under-activated responses in the paretic leg and

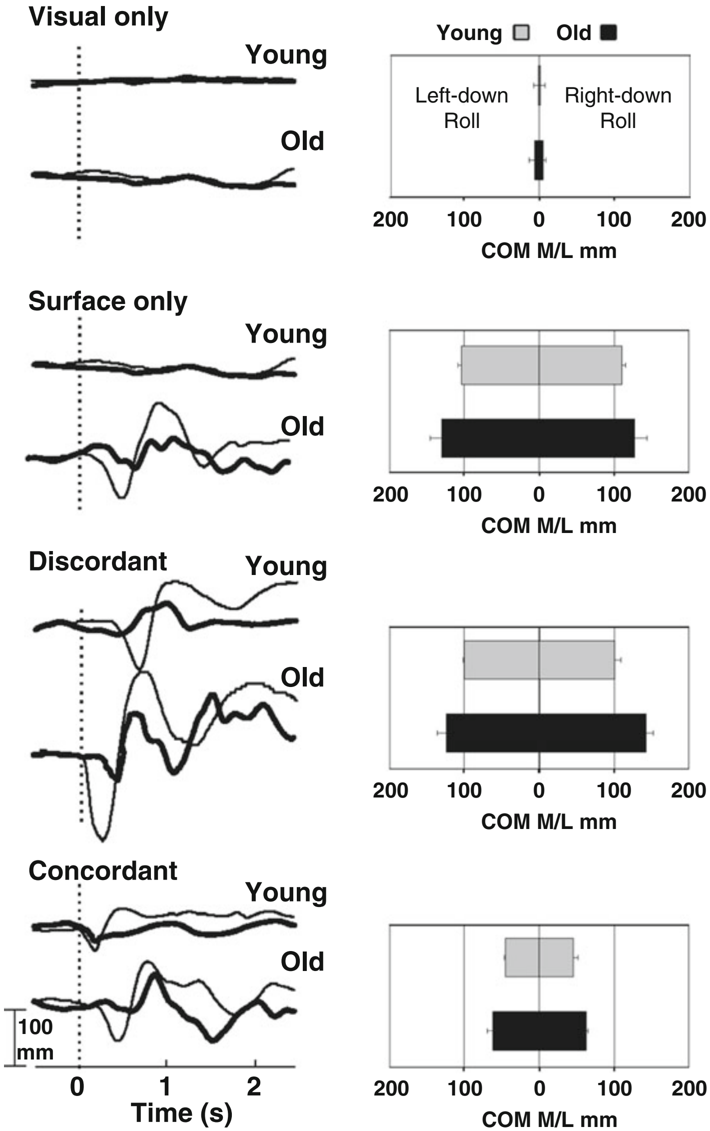
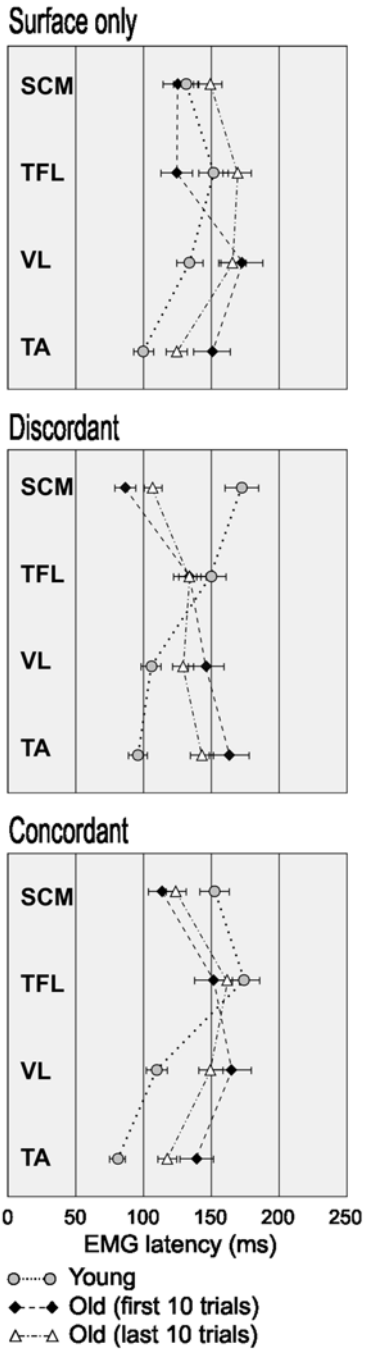


Fig. 9.8 Representative example of individual traces of COP (*thin lines*) and COM (*thick lines*) from one young and one old subject (*left panel*) exposed to right-down roll of the surface. Bar graphs on the *right panel* show COM peak-to-peak excursions (mean ± SD) averaged across 10 young subjects (*gray bars*) and 10 older subjects (*black bars*) in both left-down (*left column*) and right-down roll (*right column*) directions

exaggerated responses in the non-paretic limb (Fig. 9.11). In general, aging disrupted the distal-to-proximal muscle recruitment sequence and the presence of sensory conflict and stroke exacerbated the inconsistencies.

Fig. 9.9 EMG latencies (mean ± SD) of ventral muscles responding to toes-up pitch surface perturbations across young (*gray circles*) and old subjects. Note the decrease in the latencies in old subjects from the first 10 (*black diamonds*) to the last 10 (*open triangles*) trials



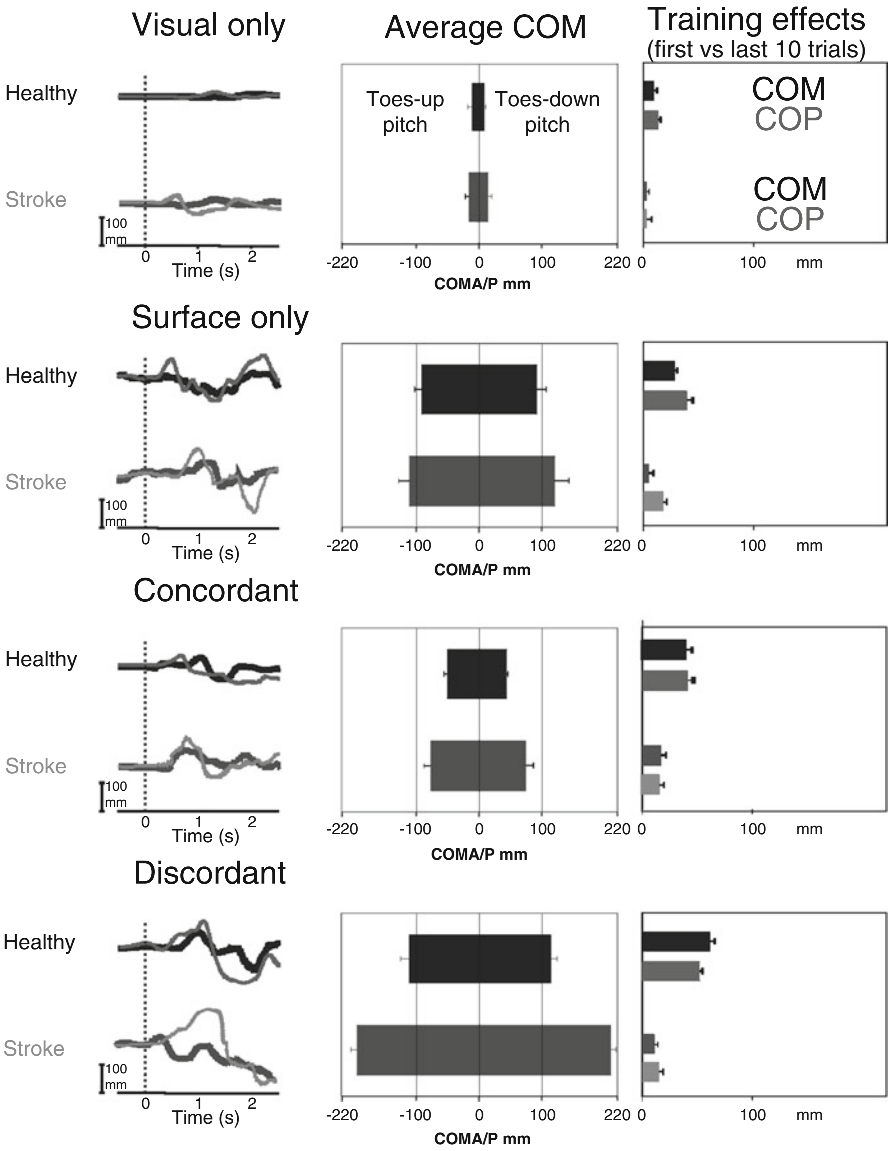


Fig. 9.10 Representative example of individual traces of COP (*thin lines*) and COM (*thick lines*) from one control healthy and one stroke subject (*left panels*) exposed to pitch plane tilt (toes-up). Bar graphs on the *middle panels* show COM peak-to-peak excursions (mean ± SD) averaged across groups of subjects in both directions of perturbations. Bar graphs on the right panels show data differences between first and last 10 trials

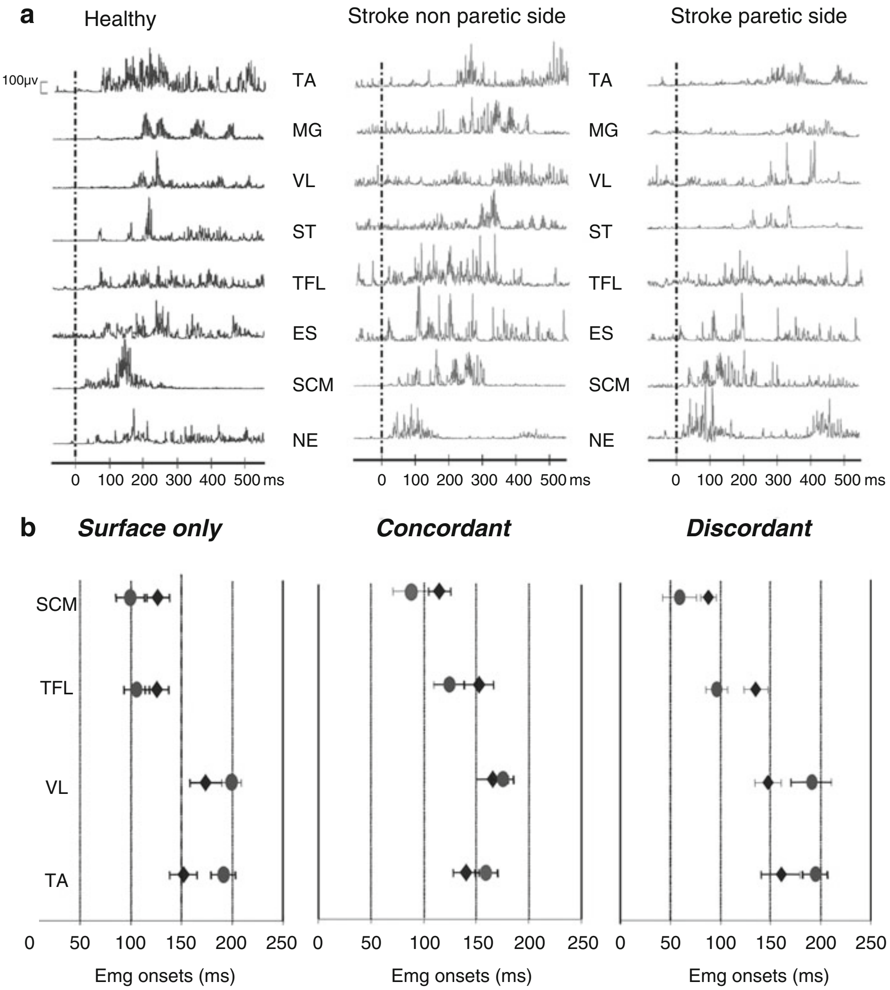


Fig. 9.11 (**a**) Example of muscle activation sequence following toes up rotation in a healthy control subject (*left panel*) and in stroke patient non paretic side (*middle panel*) and paretic side (*right panel*). (**b**) Group Mean ± SD for muscles onset latencies following pitch rotations (toes-up) for healthy control subjects (*black diamonds*) and stroke subjects (*gray circles*) in different sensory conditions: surface only, concordant and discordant in *left*, *middle* and *right panels*, respectively

The frequency-response function of each one of the four sensory conditions (Fig. 9.12) showed that young adults displayed low visual gains and high values of surface gains. In conditions of visual–somatosensory conflict, they increased surface gain and decreased visual gain, suggesting that young adults deal with the sensory conflict by either attempting to suppress visual information or attributing more weight and increased reliance on somatosensory feedback. Healthy older subjects and stroke patients displayed higher visual gains than young adults regardless of the sensory conditions. Moreover, in conditions of sensory conflict, they adopted

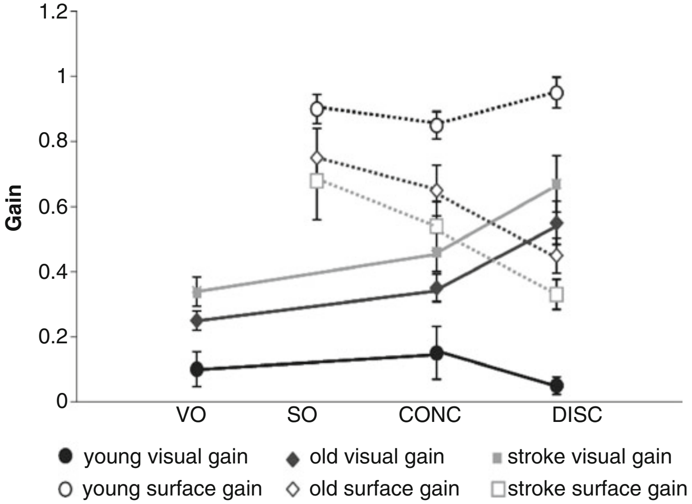


Fig. 9.12 Group Mean ± SD for COM gain relative to visual (*filled symbols*) and surface stimulus (*open symbols*) in four different sensory conditions, for healthy young (*circles*), old subjects (*diamonds*) and stroke patients (*squares*)

an opposite strategy increasing the visual gain and lowering the surface gain. This demonstrates an excessive reliance on visual inputs or a need to first stabilize their head, a common strategy adopted by people with balance impairments.

The resolution of sensory conflict is affected by aging and stroke but can be enhanced by training. Repeated exposure to VR-induced sensory conflict improved balance performance in all healthy older subjects and to some extent in stroke subjects (note differences between the first 10 trials and last 10 trials out of a total of 72 perturbation trails in Figs. 9.9 and 9.10). Even with a 1-h immersion in virtual environments and exposure to sensory conflict, it is possible for the CNS to recalibrate and adapt to the changes. A training program of longer durations is needed to confirm sustainable long-term effects.

9.7 Conclusions

Rehabilitation of postural control and balance has included practice of specific, well-defined automatic postural reactions (Horak, 2006; O'Neill, Gill-Body, & Krebs, 1998; Wrisley et al., 2007). But if relearning of postural control is to have any functional carryover, it needs to be incorporated into more complex motor behaviors (Keshner, Kenyon, & Langston, 2004; McCollum, 1999; Varraine et al., 2002). Adaptation of motor commands to functional circumstances are driven by error signals (Shadmehr, Smith, & Krakauer, 2010), and thus, the impact of rehabilitation interventions might increase if the sensory feedback can be manipulated so that it does not precisely match the expected afference.

Virtual reality is an excellent tool for presenting environments that contain controlled sensory incongruities thereby requiring constant correction to the sensory reafference (Chap. 2). The most recognized sensory characteristics of virtual reality are the absence of haptic and force feedback. But VR also creates a strong conflict between visual and vestibular senses (Lepecq et al., 2006). By adding tools such as robots (Adamovich, Fluet, Merians, Mathai, & Qiu, 2009; Qiu et al., 2010), treadmills (Kizony, Levin, Hughey, Perez, & Fung, 2010), and dynamic platforms (Keshner & Kenyon, 2004; Keshner, Kenyon et al., 2004) into the virtual environment, we can further manipulate the demands during motor tasks. Preventive and rehabilitation programs should take into account the possible impairment of sensory organization or sensorimotor integration and include VR training under conditions of sensory conflict.

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